

Development of fast, background-limited transition-edge sensors for the Background-Limited Infrared/Sub-mm Spectrograph (BLISS) for SPICA

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ABSTRACT

We report experimental progress toward demonstrating background-limited arrays of membrane-isolated transition-edge sensors (TESs) for the Background Limited Infrared/Sub-mm Spectrograph (BLISS). BLISS is a space-borne instrument with grating spectrometers for wavelengths $\lambda = 35\text{--}435\mu\text{m}$ and with $R = \lambda/\Delta\lambda \sim 500$. The goals for BLISS TESs are: noise equivalent power (NEP) = $5 \times 10^{-20} \text{ W/Hz}^{1/2}$ and response time $\tau < 30\text{ms}$. We expect background-limited performance from bilayers TESs with $T_C = 65\text{mK}$ and $G = 15\text{fW/K}$. However, such TESs cannot be operated at 50mK unless stray power on the devices, or dark power P_D , is less than 200aW. We describe criteria for measuring P_D that requires accurate knowledge of T_C . Ultimately, we fabricated superconducting thermistors from Ir ($T_C \geq 135\text{mK}$) and Mo/Cu proximitized bilayers, where T_C is the thermistor transition temperature. We measured the Ir TES arrays in our 50mK adiabatic demagnetization refrigerator test system, which can measure up to eight 1×32 arrays simultaneously using a time-division multiplexer, as well as our single-pixel test system which can measure down to 15mK. In our previous Ir array measurements our best reported performance was $\text{NEP} = 2.5 \times 10^{-19} \text{ W/Hz}^{1/2}$ and $\tau \sim 5\text{ms}$ for straight-beam TESs. In fact, we expected $\text{NEP} \sim 1.5 \times 10^{-19} \text{ W/Hz}^{1/2}$ for meander beam TESs, but did not achieve this previously due to $1/f$ noise. Here, we detail improvements toward measuring the expected NEP and demonstrate $\text{NEP} = (1.3 \pm 0.2) \times 10^{-19} \text{ W/Hz}^{1/2}$ in our single-pixel test system and $\text{NEP} = (1.6 \pm 0.3) \times 10^{-19} \text{ W/Hz}^{1/2}$ in our array test system.

Keywords: transition-edge sensors, infrared spectrometer, sub-mm spectrometer, photon background-limited

1. INTRODUCTION

The Background-Limited Infrared/Sub-mm Spectrograph (BLISS) is a proposed instrument to fly on the JAXA satellite mission known as SPICA. BLISS is a broadband grating spectrometer divided into six bands spanning $35\mu\text{m}$ to $435\mu\text{m}$. In order to be photon background-limited and to optically chop the signal from 1 to 5 Hz for noise reduction, detectors on BLISS need to at least demonstrate noise equivalent power (NEP) equal to 10^{-19} W/Hz and response time τ of $\sim 150\text{ms}$. The goal for BLISS is to have $\text{NEP} = 5 \times 10^{-20} \text{ W/Hz}^{1/2}$ and $\tau < 30\text{ms}$. Membrane-isolated transition-edge sensors (TESs) are a natural candidate to meet these requirements, and we report our progress toward demonstrating these specifications in our TESs.

1.1 Expected photon noise for BLISS on SPICA

Observing from a space-based platform gives BLISS a significant advantage over ground based IR/sub-mm observatories, as the photon background noise is greatly reduced in space and the atmosphere does not absorb IR/sub-mm light from reaching the spectrometer. The expected photon power due to the SPICA telescope, the telescope baffles, the CMB, and the interstellar and interplanetary dust ranges from 0.1 aW to 3aW over the six bands of BLISS.¹ Including a safety factor of 75 to 150, the worst case photon power ranges from about 50aW to 200aW. BLISS is designed and specified so that the detector NEP is equal to the expected photon noise at the instrument without safety factor, while simultaneously having sufficient dynamic range to accommodate the safety factor. (In reality, a dual-TES approach using a Ti TES in series with the main sensing TES will be employed to guarantee dynamic range from 3000 to

15000, depending on the band.) Photon noise is generally described by shot and Bose noise according to

$$p_n^2 = 2h\langle\nu\rangle P_{opt} + \frac{P_{opt}^2}{2\langle\Delta\nu\rangle}, \quad (1)$$

where p_n^2 is the expected photon NEP squared, P_{opt} is the photon power, $\langle\nu\rangle$ is the average frequency of the light, and $\langle\Delta\nu\rangle$ is the average bandwidth of the light. The term linearly proportional to P_{opt} is the shot-noise term, while the term proportional to P_{opt}^2 is the Bose term. Given an average $\langle\Delta\nu\rangle$ for BLISS of about 250GHz ($\langle\Delta\lambda\rangle\approx 50\mu\text{m}$), the Bose term is subdominant to the shot noise, and the expected photon noise ranges from 2×10^{-20} W/Hz^{1/2} (shortest 5 λ bands) to 5×10^{-20} W/Hz^{1/2} (longest λ band). Membrane-isolated transition-edge sensors (TESs) are a natural candidate to meet the detector NEP requirement (equal to the photon NEP) and to be formatted into arrays with a reasonable resolving power for BLISS, $R=\lambda/\Delta\lambda\sim 500$, which will require about 4000 TESs readout with a time-domain multiplexer.

The spectroscopic line sensitivity of far-IR/sub-mm spectrometers determines the ultimate performance and ability to meet the BLISS scientific objectives. The matching of the TES detector NEP_{det} to the photon background NEP_{opt} given an instrument with $R\sim 500$, leads to the best possible performance. BLISS will be an instrument coupling one polarization at a time and chopping the signal between two spectrometers. SPICA can be expected to provide 75% aperture efficiency on a 3.5m telescope for the effective area and $\eta_{inst}=25\%$ is an estimate of the end-to-end transmission through a spectrometer. This estimated value of η_{inst} is based on the performance of spectrometers such as Z-spec and IRS on Spitzer, which are similar to the spectrometers that will fly on SPICA.^{2,3} The 5σ -2hour line sensitivity assuming 5×10^{-20} W/Hz^{1/2} for all 6 is designed to have a line sensitivity of 10^{-20} W/m².

1.2 Experimental design criteria for TES testing

The expected NEP for TESs is given by

$$NEP = \sqrt{4k_B T_C^2 G \gamma} \quad \text{and} \quad \gamma = \frac{n+1}{2n+3} \frac{(1-(1-t)^{2n+3})}{(1-(1-t)^{n+1})}, \quad (2)$$

where k_B is Boltzmann's constant, G is the thermal conductance of the TES support beams, T_C is the transition temperature of the superconducting thermistor on the TES, G varies with T according to $G\sim T^n$, and γ accounts for thermal gradients along the support beams. Here, t is $1-T_{op}/T_C$, where t_{op} is the operating temperature of the TES. Given a space-qualified cryocooler operating at 50mK, a $T_C=65\text{mK}$, and $G\sim T^{1/2}$ for BLISS TESs¹, we expect to meet the NEP goal at 15fW/K.

The heat flow from the TES membrane to the substrate, while operating the TES within the transition at T_C , may be modeled by:

$$P_{flow} = K(T_C^{n+1} - T_{op}^{n+1}), \quad G = \frac{dP_{flow}}{dT}, \quad (3)$$

where K is a constant that may be related to G . A background-limited TES at margin will have a heat outflow of 200aW at 50mK. Thus, the stray power, or dark power P_D , needs to be $<200\text{aW}$ to operate at 50mK, because this P_D is the maximum heat outflow that can flow out of the device support beams without driving the TES from within the transition to the normal state. Optical and electrical sources contribute to P_D , which include stray optical radiation, SQUID amplifier Josephson oscillations acting back on the TES, and stray electrical power coming down the bias lines.

2. EXPERIMENTAL SETUP

2.1 BLISS dark testing: single-pixel and array test setups

We employ two testing systems to characterize TESs for BLISS: a single-pixel dilution refrigerator setup and a multiplexed array test system utilizing a dual-stage adiabatic demagnetization refrigerator (ADR) with 1K and 40mK stages. The single-pixel test system has a base temperature of 15mK, while the ADR array test system has a base temperature of 45mK. Both test systems utilize the typical voltage-biased setup for operating a TES within the transition at T_C using negative electrothermal feedback (ETF).⁴ A single SQUID amplifier reads out the current through the TES in the single-pixel test system, and 1.5m Ω shunt resistors are used to bias the TES. A SQUID time-domain multiplexer (TDM) is utilized in the array test system. The multiplexed SQUID chips and shunt chips needed to operate the TDM were provided by NIST. We installed two varieties of MUX chips, denoted as MUX05 and MUX09 chips⁵, as well as two types of shunt chips with 160 $\mu\Omega$ and 3m Ω impedances. A general rule is that the shunt resistance should be less than or equal to 1/10 of the normal state resistance R_N of the TES superconducting thermistor. Our Ir TESs had $R_N \sim 55\text{m}\Omega$, while our Mo/Cu TES had R_N of 7m Ω to 14m Ω , thus different shunt chips were necessary. We denote the shunt chips as NYQ chips, as the inductances are typically chosen on these chips to reduce aliasing penalties using analysis regarding the Nyquist sampling frequencies in typical operation of the TDM system.

Both test systems have means to mitigate stray optical/electrical power from affecting the TES operation. As has been reported previously, we employ attenuating coaxial bias lines, a light-tight Nb can, and RF filters at 1.9MHz and 300MHz in our single-pixel test system, and we can achieve $P_D < 250\text{aW}$ in this test system.⁶ In our current array test system, we employ a light-tight Nb box, whose electrical feed-through connections are sealed with In gaskets, to shield the TESs from stray optical light. To combat stray electrical power, we employ electrical filters fabricated on Si for stray electrical noise reduction. Both filters are cascaded three times, and the L/C filter rolls-off at $f=15\text{MHz}$, while the L/R filter rolls-off at $f=150\text{kHz}$. The narrower noise bandwidth for the L/R filter led to $P_D \sim 1\text{fW}$, while the L/C filter demonstrated $P_D \sim 5\text{fW}$ from previous measurements.⁷ We have recently tested Eccosorb⁸ on top of the L/R filter to absorb RF optical radiation in order to reduce optical stray light. The Eccosorb separated by a Nb partition from the arrays. However, we observed that many devices did not transition in this setup, which we believe is due to stray magnetic field leaking to the TES arrays despite the partition. We have subsequently removed the Eccosorb. Additionally, we built new L/R filters with expected roll-off around 20kHz with reduced inductance ($\sim 7\mu\text{H}$) compared to the previously used L/R filters ($\sim 21\mu\text{H}$) to increase bandwidth and operating range for diagnostic purposes.

2.2 Determining P_D

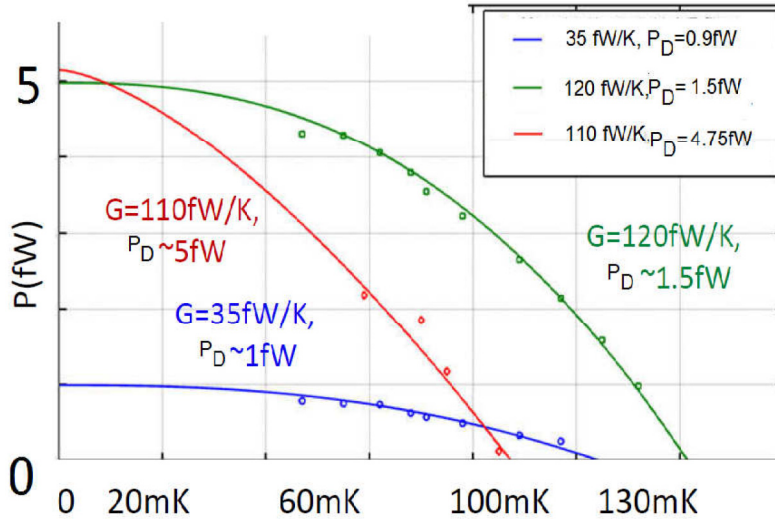


Figure 1: Examples of measured P vs. T curves for Ir TESs with different G values and the different saturation temperatures that arose from different values of P_D . We have observed that the 135mK T_C of our XeF_2 etched devices is not affected by the longitudinal proximity effect down to 10 μm wide devices in independent R vs. T measurements.

In our previous measurements, we have demonstrated the ability to measure P_D using both Johnson noise Thermometry Devices (JTDs) and TESs in the same experimental setup. A JTD employs two thin-film resistors, one is used as a thermometer and one is used as a heater, in order to measure G and heat capacity C of the membrane-isolated JTD structure as a function of temperature. Typically, the JTD is built out of Si_xN_y (Si-N) support beams and with an Si-N absorber similar to the desired TES architecture of BLISS TESs or TESs for similar instruments. This setup allows the thermal structure to be diagnosed over a larger temperature range. A measurement with a JTD in the same setup as a TES is straightforward, as the P_D incident on a TES may be estimated from the value of P_D on the JTD. A JTD measures P_D using the measured G at the lowest temperature of operation and by measuring the apparent temperature on the JTD thermometer versus the base temperature of the test system. More details may be found in Ref.[6].

Our array test system does not employ a JTD, as the many electrical connections designed to connect to the MUX/NYQ chips are not compatible with JTD measurements. Alternatively, the value of P_D in the array test system may be determined from an accurate determination of T_C for the superconducting thermistor on the TES. In our previous measurements on Ir TESs with $T_C=135\text{mK}$, we found P_D from $\sim 1\text{fW}$ to $\sim 5\text{fW}$.⁷ The values of P_D were determined from the shifting of the outflow power P_{flox} (Eq. (4)) curve of a TES according to

$$P_{\text{observed}} = K(T_C^{n+1} - T_{\text{op}}^{n+1}) - P_D. \quad (4)$$

With accurate knowledge of T_C , determination of P_D from equation (5) may be found by fitting P_{observed} as a function of T and by using a value of n known for device architecture. For our Ir TESs released by XeF_2 , the value of T_C is robust over time and size of the thermistor, and P_D is accurately determined. Without knowledge of T_C , the apparent value of T_C may easily be confused with the base temperature at which P_D alone is enough to drive the TES into the normal state. An example of different values of P_D and their effect on Joule power P as a function of T for Ir devices with varying G values is shown in Fig. 2.

2.3 Complications in determining P_D for bilayer samples

BLISS will ultimately deploy with bilayer superconducting thermistors, with the bilayer T_C tuned via the proximity effect to $T_C=65\text{mK}$. The proximity effect arises when a thin superconducting film and a thin normal metal film are fabricated in contact with each other, and the resulting bilayer T_C may be made smaller than T_C of the superconducting film alone by tuning the thicknesses of the two layers. Here, thin is generally regarded as a thickness less than the coherence length of the superconducting film.

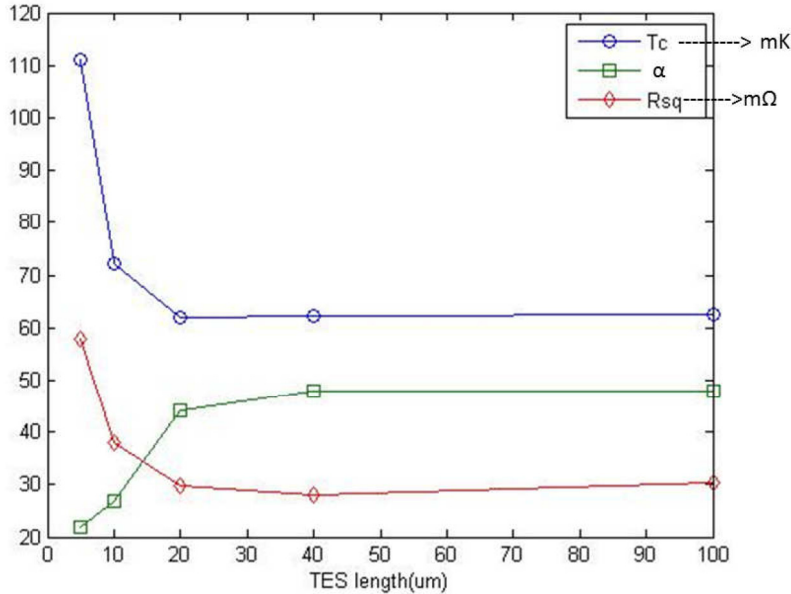


Figure 2: Average values of T_C , α , and R_{sq} (resistance per square) as a function of TES length for our Mo/Cu $T_C \approx 60\text{mK}$ recipe. T_C is displayed in mK, α is dimensionless, and R_{sq} is in mΩ.

We have developed a recipe for Mo/Cu bilayers with lower $T_C=60\text{mK}$; however, longitudinal proximity effects (LPEs)⁹ raise T_C above our target T_C for shorter TES lengths. Short TES lengths are needed to produce fractional square thermistors with low R_N for improved responsivity, reduction of multiplexing penalties, and to fit into our Si-N support architecture. Additionally, the sharpness of the superconducting transition at T_C , denoted by $\alpha=d\log R/d\log T$, is also degraded for shorter thermistor lengths. The sharpness is important in achieving the speed goals of BLISS, as the electrothermal feedback speeds up the device below the natural thermal time constant $\tau_0=C/G$ to $\tau_{\text{eff}}=\tau_0/(1+P_J\alpha/GT)$, where P_J is the Joule power on transition. Previously reported analysis using the Usadel equation¹⁰ provides a framework for modeling the T_C for a bilayer and a general physical understanding. The Usadel equation was summarized to be

$$T_C = T_{C0} \left(\frac{d_s}{d_0} \frac{1}{1.13(1+1/a)} \frac{1}{t'} \right)^a; \quad d_0 = \frac{\pi}{2} k_B T_{C0} \lambda_F^2 n_s; \quad a = \frac{d_n n_n}{d_s n_s}, \quad (5)$$

where T_{C0} is the transition temperature of the superconducting film alone, d_s is the superconducting film thickness, d_n is the normal metal film thickness, n_n and n_s are the density of states of the normal metal and superconducting films, t' is the transmission coefficient, and λ_F is the Fermi wavelength.

The actual value of T_C , R_N and α for a given thermistor are sensitive to geometry due to the LPE. The LPE can be thought of as an unintended proximity effect between the TES thermistor and the superconducting wiring used in the electrothermal circuit to readout the TES. The edges of the thermistor become superconducting due to the proximity of the wiring, which has a higher T_C than that of the bilayer, raising the temperature at which the thermistor shorts out. We have developed a recipe for $T_C=60\text{mK}$ using Mo/Cu bilayers.. However, we have discovered that T_C increases from 60mK up to 110mK as the width of the thermistor is decreased below 20 μm down to 5 μm , as shown in Fig. 3

2.4 Determining P_D for BLISS TESs

Given the complications from the LPE, we continue to use XeF_2 released Ir arrays for the thermistors, as these elemental superconductors have not demonstrated that the LPE produces a different $T_C=135\text{mK}$ between a thermistor of 100 μm length versus that from a 10 μm wide film. The arrays for Ir are the same design reported in Ref.[7], where 1mm long straight beams and 2mm long meander beams are compared. In our single-pixel test system, both types of devices can be measured. For our array test system, we had to speed up the devices using a BOE dip to remove a SiO_x layer protecting the devices from XeF_2 for improved speed. Such devices exhibited a $R_N \sim 100\text{m}\Omega$, about double that of the devices released using only XeF_2 (55m Ω). Notably, T_C exceeded 160mK, suggesting an increased value due to thinning of the Ir or another interaction with the BOE.

3. RESULTS

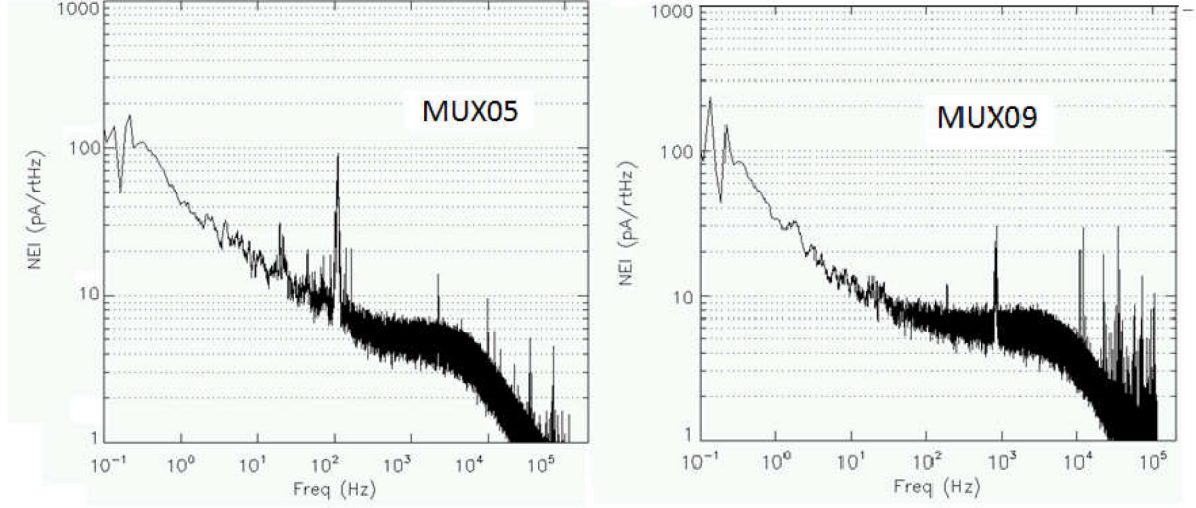


Figure 3: A comparison of the SQUID noise in our setup with TDM MUX chips from 2005 and 2009. We refer the reader to Ref. [5] for more details on the differences in design. We are working to identify the source of the large 1/f noise in our setup.

Previously, we had been unable to measure $NEP=1.5 \times 10^{-19} \text{ W/Hz}^{1/2}$ in our array test system, as was expected to be observed for the Ir meander TESs. In order to investigate the source of this issue, we measured the amplifier noise in the MUX05 and MUX09 chips in our array test system. We discovered a large 1/f signal with noise equivalent current $NEI=100 \text{ pA/Hz}^{1/2}$ at 0.1Hz and $40 \text{ pA/Hz}^{1/2}$ to $50 \text{ pA/Hz}^{1/2}$ at 1Hz, as shown in Fig. 3. Given that we expect the NEI as we enter the transition at high R to be given approximately by $\sqrt{(4k_B T_C / (R_N/2))} \sim 17 \text{ pA/Hz}^{1/2}$, our devices must be much faster than 1Hz before we will see this noise above the amplifier/system noise. Otherwise, we will have to drive the devices to much lower values of R, where there is a danger of the device becoming unstable and switching to the superconducting state.¹¹

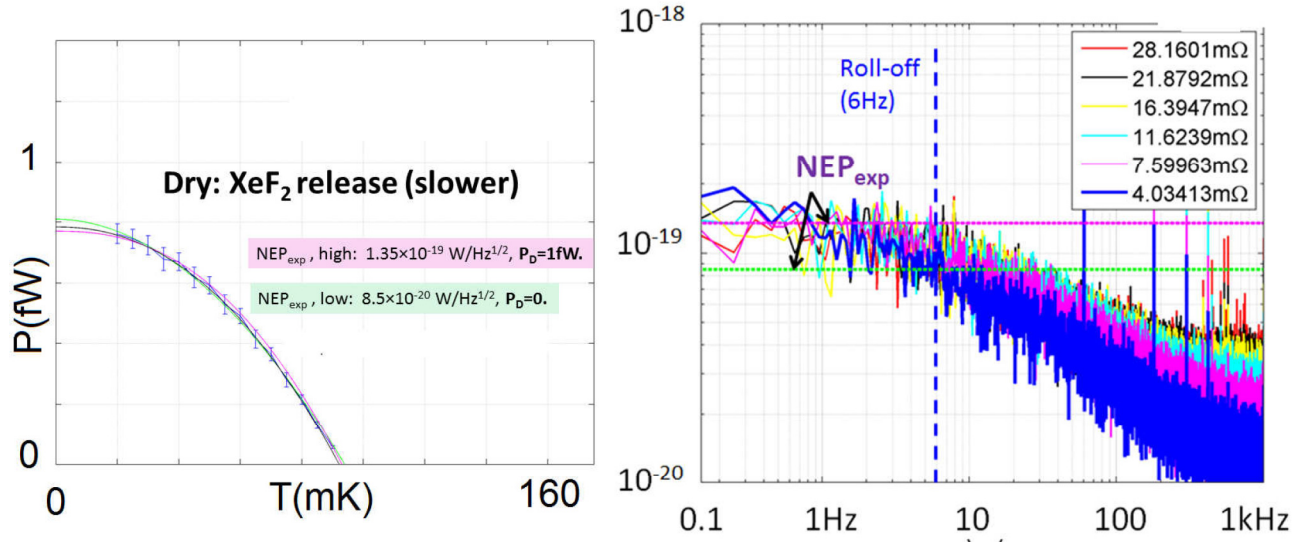


Figure 4: (Left) Measured values of the Joule power P versus temperature in a TES released by XeF_2 only. We find $G=(25\pm 8)\text{fW/K}$, $n=(1.2\pm 0.2)$, and $T_C=(120\pm 20)\text{mK}$ from fitting the data with Eq. (4). The solid lines illustrate fits to the data using Eq. (4): (1) the best fit is shown in blue; (2) the maximum expected NEP is shown in magenta; (3) the minimum expected NEP is shown in green. The estimated value of P_D varied between 0—1fW, with the best fit giving $P_D=800\text{aW}$. (Right) We measured a response time of $\sim 25\text{ms}$ in the transition, producing an expected roll-off at $\sim 6\text{Hz}$. We estimate the measured $\text{NEP}=(1.3\pm 0.2)\times 10^{-19}\text{W/Hz}^{1/2}$ from our data. The resistances shown in the legend are the values of R within the transition for each shown NEP curve.

In our single-pixel test system, we measured TES load curves and converted them into power versus resistance curves for a XeF_2 released, meandered Ir TES. From the load curves, we were able to obtain the power needed to bias the TESs within their transition (P). The resulting power versus temperature curve, along with error bars due to the uncertainty in P are shown on the left side of Fig. 4. From such a plot and using the uncertainty in P , we find $G=(25\pm 8)\text{fW/K}$, $n=(1.2\pm 0.2)$, and $T_C=(120\pm 20)\text{mK}$ from fitting the data with Eq. (4). The solid lines in Fig. 4 illustrate fits to the data using Eq. (4). The best fit is shown in blue. We also include the fits that accommodate the error bars in the data and generate the maximum (magenta) and minimum (green) expected NEP. The value of n is consistent with the crossover from $G\sim T^3$ at high temperatures to $G\sim T^{1/2}$ at low temperatures expected for BLISS devices.¹ The estimated value of P_D varied between 0—1fW. The best fit estimates P_D at 800aW for this measurement. The NEP measured was computed by multiplying the measured NEI plots multiplying by the simplified expected response $V_{\text{bias}}(R-R_{\text{sh}})/R$, where V_{bias} is the voltage bias on the device, R is the TES resistance within the transition, and R_{sh} is the shunt resistance. We measured a response time of $\sim 25\text{ms}$ in the transition, producing an expected roll-off at $\sim 6\text{Hz}$. From the plot of NEP versus frequency on the right of Fig. 4, we estimate the measured $\text{NEP}=(1.3\pm 0.2)\times 10^{-19}\text{W/Hz}^{1/2}$.

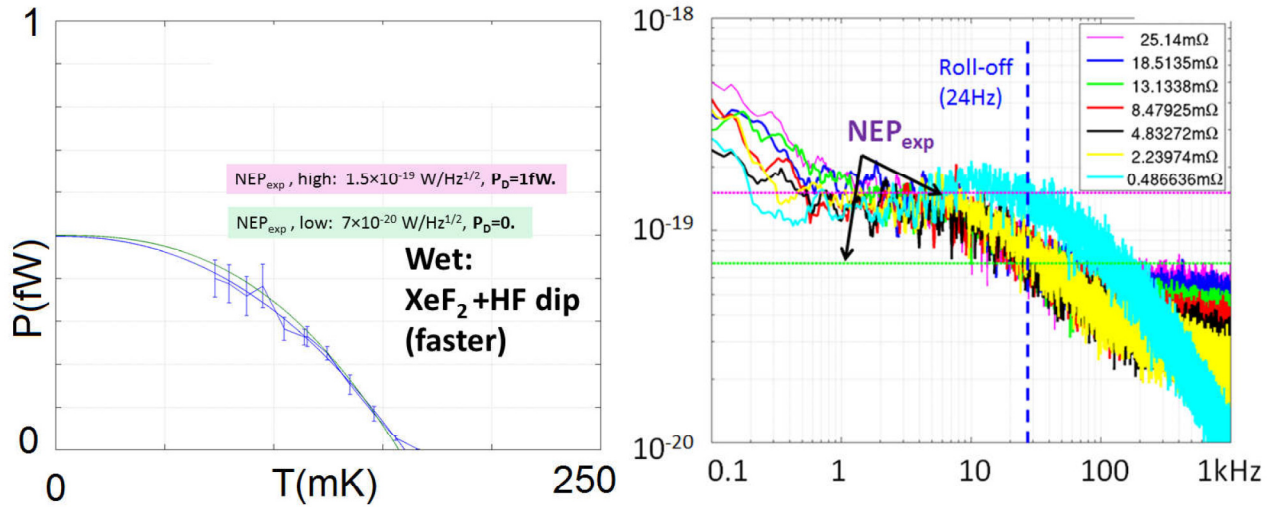


Figure 5: (Left) P vs T curves for a XeF_2 released and BOE (HF) dipped, meandered Ir TES. We find $G=(15\pm 8)\text{fW/K}$, $n=(1.4\pm 0.2)$, and $T_C=(205\pm 45)\text{mK}$ from fitting the data with Eq. (4). We observed that the normal state resistance of the device was $100\text{m}\Omega$ and $T_C \geq 160\text{mK}$, indicating an effect from the BOE. The error bars in P_j are shown with fits to the maximum (green) and minimum (blue) expected NEP from Eq. (4). P_D in the fits varied between 0 — 1.1fW . (Right) An excess noise bump near 24Hz implying a factor of 4 increase in speed due to the BOE dip. The measured NEP was $(1.6\pm 0.3)\times 10^{-19}\text{W/Hz}^{1/2}$ for this device. The resistances shown in the legend are the values of R within the transition for each shown NEP curve.

In our array test system, we measured TES load curves and converted them into power versus resistance curves for a XeF_2 released and BOE (HF) dipped, meandered Ir TES. We scanned the array and picked the device with the lowest value of G observed. The resulting power versus temperature curve, along with error bars due to the uncertainty in P are shown in the left side of Fig. 5. We find $G=(15\pm 8)\text{fW/K}$, $n=(1.4\pm 0.2)$, and $T_C=(205\pm 45)\text{mK}$ from fitting the data with Eq. (4). We observed that the normal state resistance of the device was $100\text{m}\Omega$, almost double that of the typical R_N value of the XeF_2 released Ir TESs of $55\text{m}\Omega$. We attribute the larger R_N and increased T_C to the BOE dip, which most likely thinned the thermistor. The error bars in P , as well as the fits to the maximum (green) and minimum (blue) expected NEP are also shown on the left of Fig. 5. The estimated value of P_D varied between 0 — 1.1fW with no real distinction between the 0fW and 1.1fW fits. The NEP measured was computed in the same way as described above. The excess noise bump near 24Hz suggests roll-off occurs near this frequency, indirectly showing a factor of 4 increase in speed due to the BOE dip. The measured NEP was $(1.6\pm 0.3)\times 10^{-19}\text{W/Hz}^{1/2}$ for this device.

In conclusion, we have measured NEP levels extremely close to the requirement level of BLISS at $10^{-19}\text{W/Hz}^{1/2}$. The speed of the TES measured here are for TESs with no absorber—we simply used a Si-N platform with enough space to accommodate the thermistor. The absorbers for BLISS resemble ladders (see Ref. [1]). We estimate a roll-off in response at about 5Hz to 6Hz for the largest band of BLISS, which is accomplished by scaling the size of the thermistor platform to that of the entire volume of Si-N expected in the largest band of BLISS including the thermistor platform and the ladder-like absorber. Achieving a lower NEP can be accomplished by producing Ir thermistors with T_C close to that of the bulk at 112mK , while maintaining the level of speed observed in the BOE dipped devices. We will investigate this possibility. New Mo/Cu devices with lower T_C and smaller R_N will be further investigated to achieve the goal NEP and speed necessary for BLISS. Finally, we are working to measure the stray power in our SQUID amplifiers to see if they are the source of the $\sim 1\text{fW}$ observed here. Determining the source of the stray power will be crucial in order to achieve $P_D < 200\text{aW}$.

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